

**The cognitive performance of Australian volunteer firefighters during a simulated  
wildland tour: The impact of sleep restriction and temperature.**

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## Summary

Firefighting exposes personnel to physical activity, heat and sleep restriction, however the effects of these stressors on cognitive performance have not been studied in wildland firefighters. This study aimed to determine the effects on firefighter's cognitive performance of a three-day, four-night wildland fireground tour simulation. Fifty-nine volunteer firefighters (age:  $37.1 \pm 14.8$  years, mean  $\pm$  SD) were assigned to one of three conditions: control ( $n = 23$ ), sleep restriction (SR) ( $n = 25$ ), or sleep restriction plus heat (SR+H) ( $n = 11$ ). The protocol consisted of a baseline/experimental day one (E1) with 8 h TIB followed by two experimental days (E2, E3) with 8 h TIB for control condition or two sleep restriction days (SR1, SR2) with 4 h TIB for SR and SR+H conditions. Results for PVT mean reciprocal RT showed a decline in the SR and SR+H conditions over E2/SR1 and E3/SR2 and lapses increased in all conditions by E3. For the Stroop task RTs to incongruent colour-words by E3/SR2 improved in all conditions with an increase in the percentage of errors in the SR+H condition. For the Go/Nogo task RTs on Go responses increased in all conditions by E3/SR2. Go percentage correct also declined by SR2 relative to SR1 in the SR condition only. For Stroop inhibitory control all conditions improved by E3/SR2. In contrast Go/Nogo response inhibition showed significant impairment for the SR+H condition by SR2 relative to SR1. The findings showed impaired cognitive function for both measures of automatic responding and executive function with either sleep restriction alone or combined with heat.

## KEYWORDS

sleep restriction, heat, firefighter, cognitive performance, executive function, physical activity

## 1. INTRODUCTION

Wildfires expose firefighting personnel to multiple occupational and environmental stressors, including restricted opportunities for sleep between consecutive shifts, long work hours and high environmental temperatures (Aisbett, Wolkow, Sprajcer, & Ferguson, 2012; Cater et al., 2007; Cuddy, Ham, Harger, Slivka, & Ruby, 2008). Studies on the effects of these stressors in combination in the laboratory and the field are sparse (Aisbett et al., 2012). The only studies on firefighters' cognitive performance reported small to no effects on reaction time (RT) or accuracy in response to live firefighting drills (Smith, Manning, & Petruzzello, 2001) and in different configurations of firefighting equipment (Smith & Petruzzello, 1998). Given the gap in literature on firefighting, it is useful to examine laboratory studies of the effects of sleep loss, heat, and/or physical activity, individually and in combination, on cognitive performance.

It is widely established that sleep loss affects performance on lower-level cognitive processes such as automatic responding on the Psychomotor Vigilance Test (PVT) by delays in RT and an increase in lapses. PVT performance impairments have consistently been shown from 7-14 consecutive nights of sleep restriction (Belenky et al., 2003; Dinges et al., 1997; Van Dongen, Maislin, Mullington, & Dinges, 2003). PVT performance decrements from lesser durations of only two nights of sleep restriction have also been shown (Drake et al., 2001; Swann, Yelland, Redman, & Rajaratnam, 2006). Even a single night of partial sleep deprivation individually (Innes, Poudel, & Jones, 2013; Schwarz et al., 2013) and in combination with heat and physical activity (Tokizawa et al., 2015) impacts PVT performance.

Although the effects of sleep restriction individually or combined with other stressors on PVT performance have been widely studied, there has been less research examining the

effects of sleep restriction on higher-order cognitive tasks relying on executive functions such as response inhibition. Response inhibition or inhibitory control is the function necessary to prevent or withhold the initiation of an automatic or pre-potent response when that response is no longer necessary (Drummond, Paulus, & Tapert, 2006). The Stroop and Go/Nogo tasks are two widely cited measures that assess inhibitory control, although results from sleep restriction studies often present contrasting findings (Balkin et al., 2004; Stenuit & Kerkhofs, 2008) or null results (Rossa, Smith, Allan, & Sullivan, 2014; Stenuit & Kerkhofs, 2008). For example, one study reported ‘the Stroop is really sensitive to sleep restriction’ to 4 h for three nights in a sample of women only (Stenuit & Kerkhofs, 2008). In contrast, another large-scale study on the comparative utility of cognitive tests to sleep loss showed no significant effects on Stroop task measures of sleep restriction between 3 h and 9 h for 7 nights (Balkin et al., 2004). Sleep restriction to 4 h for two nights had no effect on the total number of errors on the Go/Nogo task (Stenuit & Kerkhofs, 2008). Similarly, the number of errors on an emotional Go/Nogo task was not affected following a night of 3 h sleep (Rossa et al., 2014).

Nonetheless the suggestion that sleep loss may affect performance on these tasks is supported by findings from studies of partial sleep deprivation showing decrements in Stroop task performance (Jarraya, Jarraya, Chtourou, Souissi, & Chamari, 2013) and also with time of day impairments in the morning relative to the afternoon (Jarraya, Jarraya, Chtourou, & Souissi, 2014). Similarly, Go/Nogo task performance impairments have been reported following one or two nights of complete sleep loss (Bougard, Moussay, Espié, & Davenne, 2015; Drummond et al., 2006). Time of day effects following physical exercise on Go/Nogo performance have also been reported with improved performance in the afternoon relative to the morning (Petit, Bourdin, Mougin, Tio, & Haffen, 2013). For both the Stroop and Go/Nogo tasks, heat and physical activity have also been studied with impairments in Stroop

performance shown during industrial work in the heat (Mazloumi et al., 2014), although no effect on Go/Nogo performance was reported from exercise in the heat (Ando et al., 2015).

One reason for the discrepancy in results between sleep restriction studies for the Go/Nogo task is the use of task variants of the paradigm, measuring cognitive processes other than response inhibition. For example, an emotional Go/Nogo task measures not only the ability of participants to successfully inhibit responses but also the cognitive processes of emotional regulation and impulse control (Rossa et al., 2014). Similarly, where Stroop task performance has been reported to be affected by sleep restriction it is sometimes unclear which component is being assessed. For example, reporting increased total reaction times on the Stroop task may also be inclusive of RTs for incorrect responses (Stenuit & Kerkhofs, 2008). Since performance on a task is dependent on a range of cognitive processes it is important to assess the low-level processes such as automatic responding through to the higher-order executive functions such as response inhibition whilst distinguishing between the executive and non-executive components of a task (Swann et al., 2006).

To the authors' knowledge, the effects of two or more nights of sleep restriction, heat and physical activity combined on the PVT, Stroop and Go/Nogo tasks, has not yet been studied. Furthermore, findings from sleep restriction studies have not provided consistent results for the Stroop and Go/Nogo tasks where other studies of partial sleep deprivation or a single night's sleep loss show a consistent impairment in reaction time for the PVT.

Moreover, there is a gap in research literature on cognitive performance for volunteer firefighters undertaking multi-day fire campaigns. Hence, the aim of this study was to determine whether performance on a range of cognitive tasks including the PVT, Stroop, and Go/Nogo, is affected by sleep restriction in combination with heat compared to sleep restriction alone, and if these conditions differ from full sleep opportunities. To test this aim this study utilised a controlled laboratory simulation of a three-day wildland fireground tour

including firefighter physical activities, with day- and night-time temperature manipulations and sleep loss.

## **2. MATERIALS AND METHODS**

### **2.1 Participants**

Participants were recruited from state fire agencies in Australia (Australian Capital Territory, New South Wales, South Australia, Victoria, and Tasmania). Firefighters were assigned to one of three conditions, control, sleep restriction (SR) or sleep restriction plus heat (SR+H) (demographics reported in Table 1). Ethics approval was obtained from the CQUniversity (H12/01-016) and Deakin University Human Research Ethics Committees (2010-170).

**TABLE 1** Demographics of firefighters in the control, SR and SR+H conditions. Values are in mean  $\pm$  SD.

	Control	SR	SR+H
<i>n</i>	23	25	11
Age (y)	35.2 $\pm$ 15.5	38.5 $\pm$ 13.2	37.5 $\pm$ 15.6
BMI (kg·m <sup>-2</sup> )	27.0 $\pm$ 4.6	29.2 $\pm$ 4.9	26.7 $\pm$ 4.6
Male: Female	21:2	20:5	10:1

## 2.2 Design and procedure

The three day simulated wildland fireground deployment consisted of a baseline night/experimental day one (E1) with an 8 h sleep opportunity (time in bed [TIB] 2230-0630 h). This was followed by two experimental days (i.e., E2 and E3) with either 8 h TIB (2200-0600 h) for the control condition or two sleep restriction days (i.e., SR1 and SR2) with 4 h TIB (0200-0600 h) for the SR and SR+H conditions. Single-blind procedures were used prior to participants' arrival at 1900 h on baseline night where participants were instructed on the cognitive tests completing numerous practice trials and then told their sleep condition allocation.

On E1 participants completed further cognitive task familiarisation before the baseline trial was taken at 1040 h for all cognitive measures preceding the simulated fireground shift at 1230 h. The simulated dayshift was comprised of four intermittent two hourly physical-cognitive test sessions. Each 2 h testing session consisted of a 55 min physical work circuit (PWC) involving wildland firefighter suppression tasks (for a detailed methodology (Vincent et al., 2015)), 20-25 min of physiological testing (for a detailed methodology (Larsen, Snow, & Aisbett, 2015)), and 20-25 min of cognitive testing followed by a 15-20 min rest period. For the PVT and Stroop task the trials were conducted at the same overlapping times each day 1120 h (morning trial), 1350 h (mid-afternoon trial), 1550 h (late-afternoon trial) and 1750 h (evening trial). For the Go/Nogo task, the morning trial was conducted slightly earlier at 0920 h.

For the control and SR conditions temperature was set to 18-20°C throughout the protocol. For the SR+H condition from 1130 h on E1, temperature was set to 33-35°C during the day (0600-1800 h), and 23-25°C during the night (0600-1800 h). Temperature was maintained with a wireless temperature and humidity logger (HOBO ZW\_003, One Temp



Pty Ltd, Australia), three data receivers (HOBO ZW\_RCVR, One Temp Pty Ltd, Australia) and included software (HOBO Pro Software, One Temp Pty Ltd, Australia). During the simulated dayshift participants wore personal protective clothing (approximately 5 kg) (International Organisation for Standardisation, ISO 15384:2003) including Proban® fire retardant cotton fabric jacket and trousers (Protex®, Australia), suspenders, boots, gloves, helmet, and goggles.

## **2.3 Measurements**

### **2.3.1 PVT**

The PVT is a widely accepted measure of sustained attention with a small learning curve of only 1-3 trials (Dorrian, Dinges, & Rogers, 2005). A validated 5 minute version of task (Roach, Dawson, & Lamond, 2006) was presented on the personal digital assistant Tungsten E PalmPilot (Palm Inc., Sunnyvale, California). The PVT task measures how fast participants respond to a luminous-white-light presented on a black target stimulus by pressing the correct key with their dominant hand, displaying the response time in milliseconds (ms) for 500 ms. The screen presents the visual stimulus counting from 0 to 60 sec in 10 ms intervals, with the inter-stimulus interval varying randomly between 2,000 and 10,000 ms, producing approximately 45 RTs per 5 min trial. The dependent variables (DVs) for the PVT were mean reciprocated RT (RRT i.e.,  $1/RT \times 1000$ ) and also the number of lapses (i.e., RTs > 500 ms).

### **2.3.2 Stroop task**

This task consisted of 2 x 2 min trial types, congruent and incongruent. On congruent colour-word trials the font colour of the word matches the text. On incongruent colour-word trials the font colour of the stimuli does not match the text (e.g., the word “RED” presented in blue font). For incongruent trials participants must inhibit the pre-potent response of naming the written word in order to correctly respond by naming the colour of the font. Participants were instructed to ‘respond as quickly and as accurately as possible’ by naming the font colour of stimuli via the corresponding colour on an alphanumeric keypad. Colour-word displays were made up of the words RED, BLUE, GREEN or YELLOW presented individually against a black background until a response was registered. The computerised task was presented on a standard laptop pc 17” screen (resolution, 1280p x 800p) and administered using E-prime software version 2.0. The non-executive DVs for the task were median RTs for correct responses to incongruent colour-words and also the percentage of errors. The executive function of inhibitory control was calculated as incongruent minus congruent median RTs for correct responses (Barger et al., 2014; Burke, Scheer, Ronda, Czeisler, & Wright, 2015).

### **2.3.3 Go/Nogo task**

For this task six different versions were constructed each presenting two geometric shapes of two sizes, large and small, in a homogenous colour with three of the shapes consisting of ‘Go’ stimuli and one a ‘Nogo’ stimulus. In a semi-random order one of the four shapes is shown in the centre of the screen for a period of 200ms, with a 1300ms inter-stimulus interval. Participants are required to respond with a space bar button press on the keyboard to all Go shapes and to withhold responses to Nogo shapes. Speed and accuracy were emphasised in the instructions. Each test had an average duration of 4 min 35 sec, displaying 181 images, with 63% consisting of Go stimuli. The computerised task was presented on a

standard laptop pc screen (17" screen, resolution, 1280x800p) and administered using E-prime software version 2.0. The non-executive DVs measuring automatic responding for the Go/Nogo task were RTs on correct responses to 'Go' stimuli and the percentage correct (Drummond et al., 2006). The executive function of response inhibition was measured with percentage of incorrectly withheld responses to Nogo stimuli (Drummond et al., 2006). The Go/Nogo task has shown moderate to high test-retest reliability (Weafer, Baggott, & de Wit, 2013).

#### **2.3.4 Physical activity data**

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn prior to and during the experiment, sampling movement at 32 hertz. Physical activity was measured by summing all physical activity counts generated in each 60 sec epoch during the 55 min PWC preceding each cognitive test session.

#### **2.4 Data analyses**

To assess the main and interaction effects of condition, day, and trial on cognitive dependent variables, data were analysed using a mixed model analysis of variance with 3 fixed factors of condition (3 levels— control, SR, SR+H), experimental/sleep restriction day (3 levels – E1, E2/SR1, E3/SR2) and time of day (4 levels for PVT and Stroop task – 1040 h/1120 h, 1350 h, 1550 h, 1750 h; 2 levels for Go/Nogo task - 1040 h /0920 h, 1750 h) with a random factor of participants ( $n = 59$ ) and physical activity as a co-variate. All statistical analyses were conducted using SPSS 20.0. The denominator degree freedoms for  $F$  statistics were computed

using Satterthwaite approximation method. Least significant difference (LSD) post-hoc contrasts were specified between levels of the fixed effect factors. Uncorrected degrees of freedom are reported.

### **3. RESULTS**

#### **3.1 PVT mean RRT and lapses**

There was a significant main effect of day on PVT mean RRT and lapses and also a significant interaction effect of condition by day on mean RRT (Table 2). For the main effect of day on mean RRT by E3/SR2 values had significantly decreased relative to both E1 ( $p < 0.001$ ) and E2/SR1 ( $p < 0.001$ ), when averaged over conditions and trials. For the interaction effect of condition by day on mean RRT post-hocs showed values significantly declined over E2/SR1 and E3/SR2 compared to E1 in both the SR and SR+H conditions, when averaged over trials (Fig. 1A). Additionally, mean RRT by E3/SR2 had significantly declined from E2/SR1 in the SR and SR+H conditions (Fig. 1A).

For the main effect of day on lapses by E3/SR2 values had significantly increased relative to both E1 ( $p < 0.001$ ) and E2/SR1 ( $p = 0.001$ ), when averaged over conditions and trials. Post-hoc contrasts for condition by day on lapses showed by E2/SR1 values had significantly increased compared to E1 in the SR condition and by E3/SR2 values had significantly increased relative to E1 in all conditions, when averaged over trials (Fig. 1B). Additionally, lapses by E3/SR2 had significantly increased from E2/SR1 in the SR and SR+H conditions (Fig. 1B).

#### **3.2 Stroop incongruent colour-words median RTs and percentage of errors**

287

288 Results demonstrated a main effect of day on both incongruent median RTs for correct  
289 responses and percentage of errors (Table 2). Results also showed an interaction effect of  
290 condition by day on incongruent median RTs and an interaction effect of trial by day on  
291 incongruent percentage of errors (Table 2). There was also a main effect of stimulus type  
292 (i.e., the “Stroop effect”) ( $F_{1,1725}=564.029, p < 0.001$ ) with median RTs fastest for congruent  
293 colour-words (mean =  $705.201 \pm 107.370$  SD) (results not reported) and slowest for  
294 incongruent colour-words (mean =  $856.635 \pm 153.624$  SD).

295 For the main effect of day on incongruent median RTs by E3/SR2 values had  
296 significantly decreased (i.e., improved) relative to E1 ( $p < 0.001$ ) and E2/SR1 ( $p < 0.001$ ),  
297 when averaged over conditions and trials. For the interaction effect of condition by day on  
298 incongruent median RTs post-hocs showed by E3/SR2 values had significantly decreased  
299 relative to E1 and E2/SR1, in all conditions, when averaged over trials (Fig. 2A).

300 Additionally, RTs by E2/SR1 had significantly decreased from E1 in the control and SR+H  
301 conditions, when averaged over trials (Fig. 2A).

302 For the main effect of day on incongruent errors percentage by E3/SR2 values had  
303 significantly increased relative to E1 ( $p = 0.044$ ) and E2/SR1 ( $p = 0.002$ ), when averaged  
304 over conditions and trials. Post-hoc contrasts for condition by day on incongruent errors  
305 percentage revealed values had increased significantly by E3/SR2 relative to E1/BA in the  
306 SR+H condition, when averaged over trials (Fig. 2B). Additionally, errors had significantly  
307 increased by E3/SR2 relative to E2/SR1 in the control condition and had also increased with  
308 marginal statistical significance by E3/SR2 compared to E1 ( $p = 0.056$ ) in the control  
309 condition, when averaged over trials (Fig. 2B).

310 For the interaction effect of time of day by day on incongruent errors percentage,  
311 post-hocs showed on E1 the 1040 h trial was higher in errors compared the 1550 h trial ( $p =$

0.037), when averaged over conditions. For E2/SR1 the 1350 h trial was lower in errors relative to both the 1550 h ( $p = 0.052$ ) and 1750 h trials ( $p = 0.024$ ). By E3/SR2 the 1350 h trial was higher in errors than the 1550 h trial ( $p = 0.024$ ) and the 1120 h trial was higher in errors than both the 1550 h ( $p = 0.010$ ) and 1750 h trials ( $p = 0.027$ ).

### **3.3 Go/Nogo task - Go RTs and percentage correct**

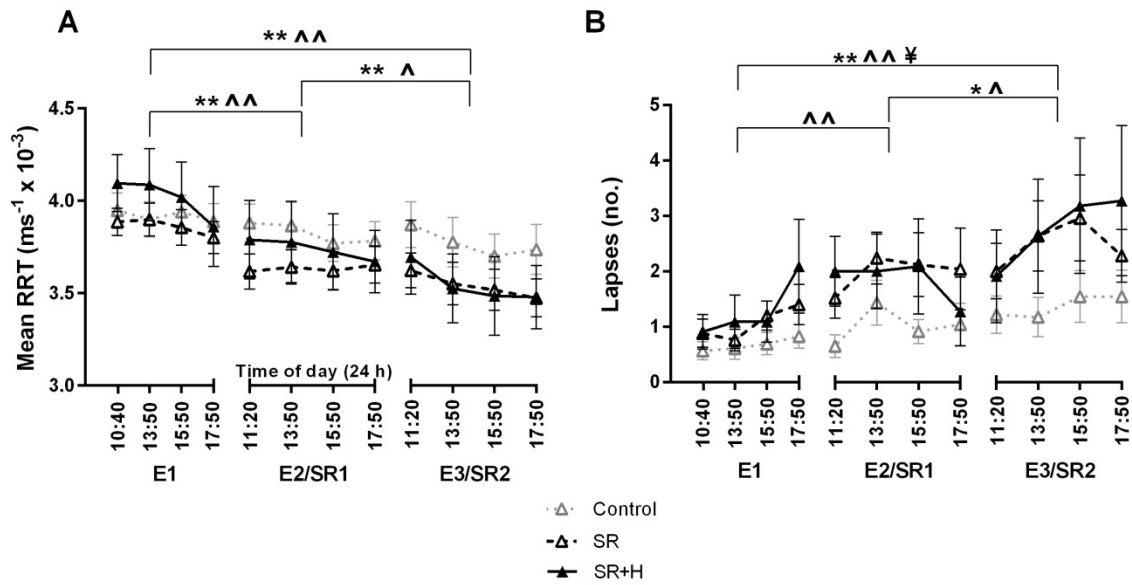
Results demonstrated a main effect of day and also an interaction effect of time of day by day on Go RTs for correct responses (Table 2). For the main effect of day on Go RTs by E3/SR2 values had significantly increased relative to both E1 ( $p < 0.001$ ) and E2/SR1 ( $p < 0.001$ ), when averaged over conditions and trials. For the interaction effect of time of day by day on Go RTs by E3/SR2 the 0920 h trial values had significantly increased compared to the 1750 h trial ( $p = 0.013$ ), when averaged over conditions. Post-hoc contrasts on condition by day for Go RTs also revealed by E2/SR1 values were significantly higher than E1 in the SR condition and by E3/SR2 values were significantly higher in all conditions compared to E1, when averaged over trials (Fig. 3A). Additionally, Go RTs by E3/SR2 were significantly higher than E2/SR1 in all conditions, when averaged over trials (Fig. 3A).

For Go percentage correct post-hoc contrasts for condition by day showed by E3/SR2 values were significantly lower than E2/SR1 in the SR condition, when averaged over trials (Fig. 3B). Post-hocs contrasts for time of day by condition on Go percentage correct showed the 1750 h trial values were significantly higher compared the 1040 h/0920 h morning trials ( $p = 0.011$ ) in the SR condition, when averaged over days. Additionally, planned contrasts for time of day by day on Go percentage correct showed by E3/SR2 the 1750 h trial values were significantly higher compared to the 0920 h trial ( $p = 0.010$ ), when averaged over conditions.

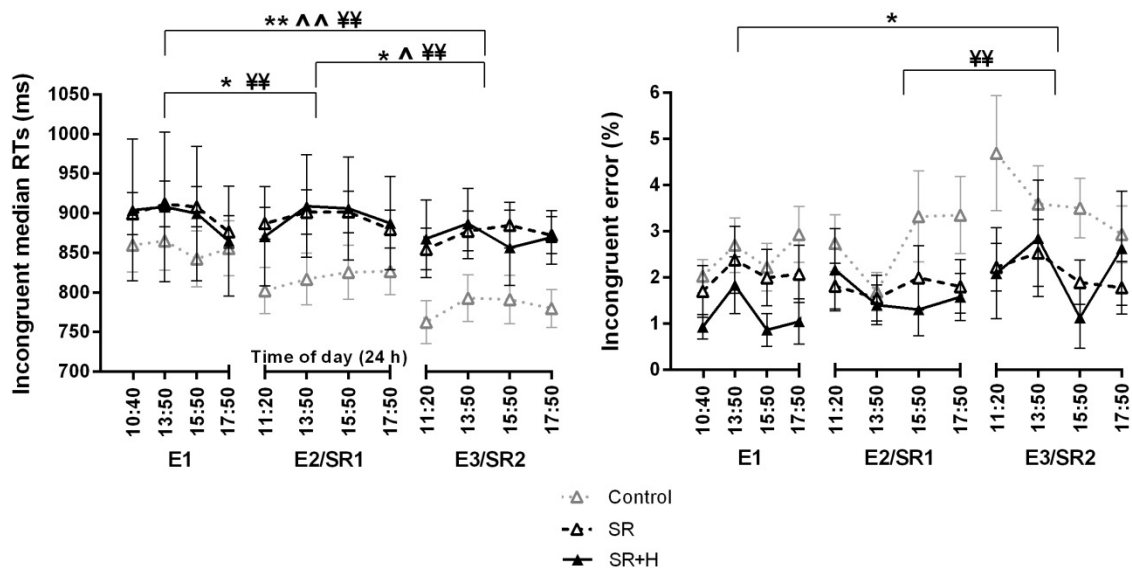
### 3.4 Executive functions: Stroop inhibitory control and Go/Nogo response inhibition

Results demonstrated a main effect of trial on Stroop inhibitory control and a main effect of day on both Stroop inhibitory control and Go/Nogo response inhibition (Table 2). For the main effect of day on Stroop inhibitory control by E3/SR2 values were significantly lower relative to E1 ( $p < 0.001$ ) and E2/SR1 ( $p = 0.002$ ), when averaged over trials and conditions. For the main effect of time of day on inhibitory control both the 1350 h and 1550 h trial values were significantly higher compared to the 1750 h trial ( $p = 0.002$  and  $p = 0.041$ , respectively), when averaged over days and conditions. Post-hocs contrasts for condition by day on inhibitory control showed by E3/SR2 values had significantly decreased (i.e., improved) in all conditions relative to E1/BA, when averaged over trials (Fig. 4A). Additionally by E3/SR2 values had significantly decreased from E2/SR1 in the control and SR+H conditions and had also declined from E1 to E2/SR1 in the control condition, when averaged over trials (Fig. 4A).

For the main effect of day on Go/Nogo response inhibition by E3/SR2 values were significantly higher (i.e., impaired) relative to E2/SR1 ( $p < 0.001$ ), when averaged over conditions and trials. Post-hoc contrasts for condition by day on response inhibition showed by E3/SR2 values were significantly higher compared to E2/SR1 ( $p = 0.004$ ) for the SR+H condition, when averaged over trials (Fig. 4B).

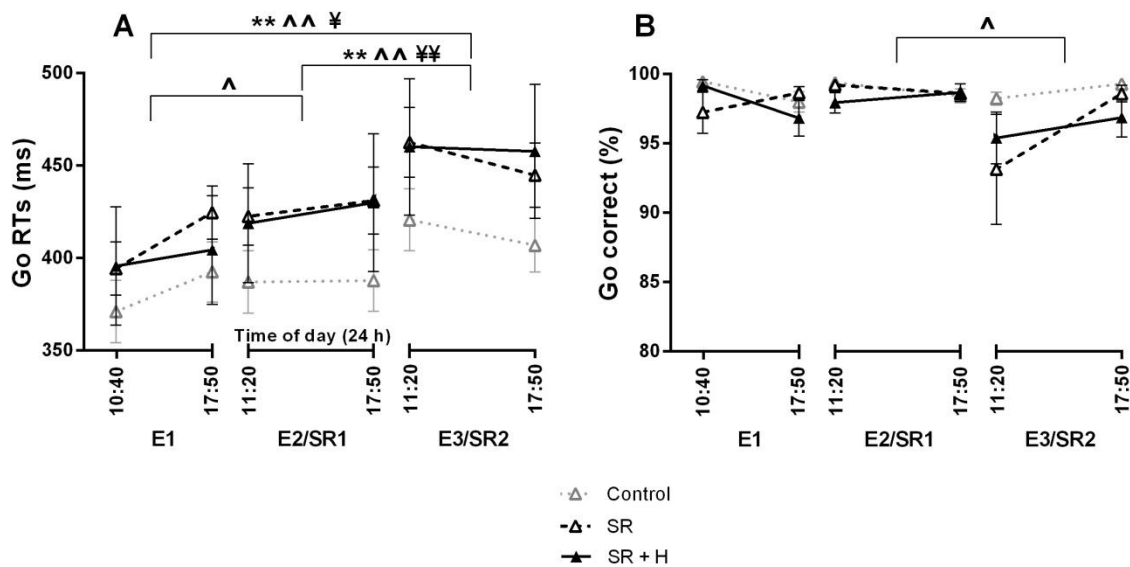


**Fig. 1** PVT. Panel A: Mean RRT. Panel B: Lapses. Plotted as day by time of day with condition. Symbols denote a significant difference for conditions between days:  $^*(p < 0.05)$ ,  $^{**}(p < 0.01)$  SR+H condition;  $^{\wedge}(p < 0.05)$ ,  $^{\wedge\wedge}(p < 0.01)$  SR condition;  $^{\text{¥}}(p < 0.05)$  control condition. Values represent mean while error bars represent standard error of the mean (SEM).

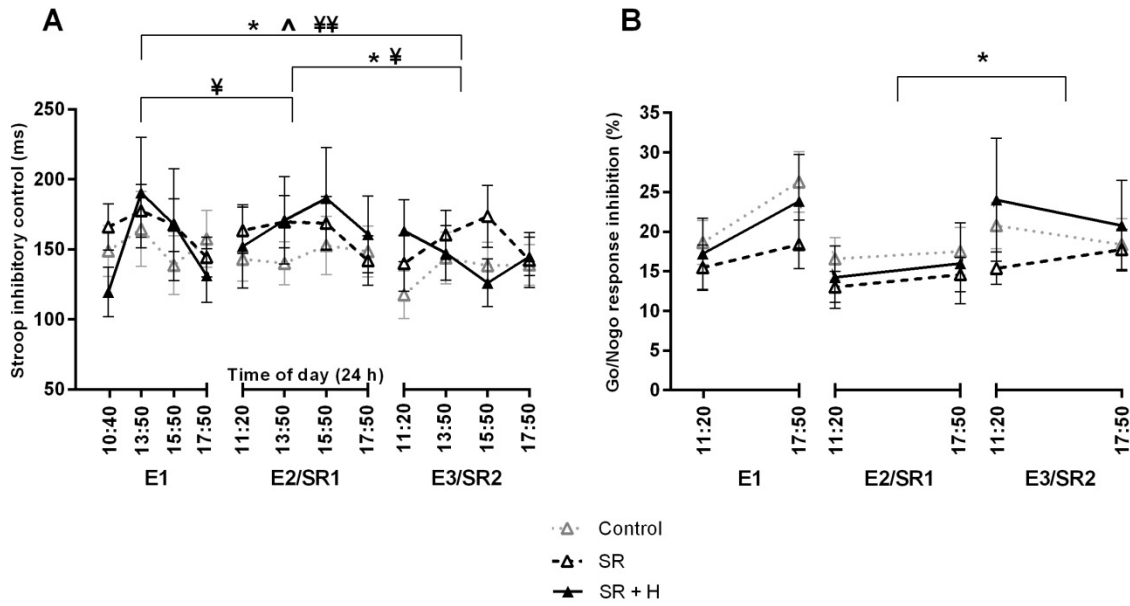




**Fig. 2** Stroop task. Panel A: Median RTs for correct responses to incongruent colour-words. Panel B: Percentage of errors on incongruent colour-words. Plotted as day by time of day with condition. Symbols denote a significant difference for conditions between days:  $^*$  ( $p < 0.05$ ),  $^{**}$  ( $p < 0.01$ ) SR+H condition;  $^{\wedge}$  ( $p < 0.05$ ),  $^{\wedge\wedge}$  ( $p < 0.01$ ) SR condition;  $^{\text{¥¥}}$  ( $p < 0.01$ ) control condition. Values represent mean  $\pm$  SEM.



**Fig. 3** Go/Nogo task. Panel A: RTs on correct responses to Go stimuli. Panel B: Percentage of correct responses to Go stimuli. Plotted as day by time of day with condition. Symbols denote a significant difference for conditions between days:  $^{**}$  ( $p < 0.01$ ) SR+H condition;  $^{\wedge}$  ( $p < 0.05$ ),  $^{\wedge\wedge}$  ( $p < 0.01$ ) SR condition;  $^{\text{¥}}$  ( $p < 0.05$ ),  $^{\text{¥¥}}$  ( $p < 0.01$ ) control condition. Values represent mean  $\pm$  SEM.



**Fig. 4** Executive function. Panel A: Stroop inhibitory control scores represent the difference between median RTs for correct responses to incongruent and congruent colour-words. Panel B: Go/Nogo response inhibition scores represent percentage of incorrect responses to Nogo stimuli. Plotted as day by time of day with condition. Symbols denote a significant difference for conditions between days: \* ( $p < 0.05$ ) SR+H condition; ^ ( $p < 0.05$ ) SR condition; ¥ ( $p < 0.05$ ), ¥¥ ( $p < 0.01$ ) control condition. Values represent mean  $\pm$  SEM.

387 **TABLE 2** Results of mixed-effect ANOVAs on PVT, Stroop and Go/Nogo tasks with fixed effects of condition, experimental/sleep restriction  
388 day, and time of day with participant ID as a random effect and physical activity as a covariate.

	Physical activity			Condition			Day			Time of day			Condition by day			Condition by time of day			Day by time of day		
	<i>F</i>	<i>df</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>
PVT RRT	1.88	1,678	.171	1.00	2,56	.375	32.52	2,651	<b>&lt;.001</b>	2.54	3,642	.056	6.99	4,628	<b>&lt;.001</b>	.52	6,625	.797	1.17	6,636	.322
PVT Lapses	.01	1,354	.929	2.50	2,56	.091	14.98	2,677	<b>&lt;.001</b>	1.34	3,653	.260	1.42	4,633	.227	.21	6,623	.872	.937	6,646	.468
Stroop RTs	2.41	1,654	.121	.156	2,55	.156	30.81	2,623	<b>&lt;.001</b>	2.76	3,618	<b>.042</b>	5.53	4,611	<b>&lt;.001</b>	.620	6,609	.715	1.31	6,615	.249
Stroop error	5.27	1,622	<b>.022</b>	1.23	2,56	.300	5.08	2,644	<b>.007</b>	1.89	3,632	.129	2.06	4,614	.085	1.36	6,609	.228	2.70	6,624	<b>.014</b>
Stroop IC	6.64	1,650	<b>.010</b>	.614	2,56	.545	9.48	2,637	<b>&lt;.001</b>	3.36	3,627	<b>.018</b>	1.02	4,612	.395	1.37	6,607	.225	1.62	6,620	.138
Go RTs	.03	1,310	.862	1.35	2,56	.267	29.54	2,291	<b>&lt;.001</b>	1.02	1,298	.313	1.43	4,281	.225	.63	2,280	.535	6.34	2,291	<b>.002</b>
Go correct	2.68	1,104	.104	2.31	2,57	.108	2.30	2,335	.102	2.43	1,330	.120	.94	4,285	.444	1.42	2,284	.244	2.57	2,337	.078
Go/Nogo RI	.51	1,337	.477	.836	2,57	.439	7.63	2,308	<b>.001</b>	3.67	1,326	.056	.89	4,282	.473	.118	2,281	.889	2.21	2,309	.112

389 Stroop RTs, median RTs for correct responses to incongruent colour-words; Stroop error, percentage of incorrect responses to incongruent  
390 colour-words; Stroop IC, Stroop Inhibitory control; Go RTs and Go correct, RTs and percentage of correct responses to ‘Go’ stimuli on the  
391 Go/Nogo task; Go/Nogo RI, response inhibition.

## 4. DISCUSSION

For PVT performance results showed mean RRT declined over sleep restriction days in both restriction conditions. Lapses increased on the first sleep restriction day in the sleep restriction condition only but differences were seen in all conditions by the final day of the experiment. For the Stroop task RTs for incongruent colour-words by the final experimental day were faster in all conditions. However, there was also an increase in the percentage of errors (i.e., a speed-accuracy trade-off) for incongruent colour-words in the sleep restriction plus heat condition. Times of day effects on percentage of errors for incongruent colour-words were evident on experimental days one and three in the morning trial by an increased percentage of errors relative to the late-afternoon and evening trials. For the Go/Nogo task RTs on correct Go responses slowed on the first day of sleep restriction in the sleep restriction condition only and then by the final experimental day Go RTs were slower in all conditions. Performance on Go percentage correct also declined by the second day of sleep restriction relative to the first in the sleep restriction condition only. Time-of day effects were also revealed for Go percentage correct with improved performance in the afternoon test relative to the morning trial, in the sleep restriction condition only when averaged over days. However on sleep restriction day two, the same time-of day effect pattern emerged irrespective of condition. For Stroop inhibitory control all conditions improved by the final day of the experiment however Go/Nogo response inhibition showed significant impairment for the sleep restriction plus heat condition by the second day of sleep restriction relative to the first.

The findings of impairments on PVT automatic measures mean RRT and lapses on the first day of sleep restriction for the sleep restriction condition only, is consistent with two recent studies showing partial sleep deprivation to 4 h resulted in impairments on PVT mean

RT and lapses (Innes et al., 2013; Schwarz et al., 2013). Although the precise day PVT performance impairments arise tends to vary between studies of sleep restriction for two consecutive nights. For example, two studies showed performance declines following the second night of sleep restriction, although not first, to either 4 h or 4.8 h on PVT median RT, mean RT and lapses (Drake et al., 2001; Swann et al., 2006). In contrast another study reported no effects following two nights of sleep restriction to either 3 h or 5 h on PVT median RT and lapses (Rupp, Arnedt, Acebo, & Carskadon, 2004).

The finding that PVT mean RRT declined following the first night of sleep restriction in the heat is also consistent with previous research on partial sleep deprivation to 4 h following exercise in 35°C heat (Tokizawa et al., 2015). Tokizawa et al. (2015) also reported the number of lapses increased following only a single night of sleep deprivation in the heat although in this present study lapses did not increase in the heat until after the second night of restriction. Nonetheless, the effect of heat by itself is unclear with other research showing no effect on PVT performance from heat with exercise (Parker et al., 2013) and also immediately following exercise in thermal protective clothing (Morley et al., 2012).

For the non-executive components of the Stroop task results showed a speed-accuracy trade-off for incongruent colour-words in the sleep restriction plus heat condition by the second night of sleep restriction in that reaction times were faster but accuracy fell. This finding is consistent with a previous study showing partial sleep deprivation to 2 h resulted in a speed-accuracy trade-off for RTs and percentage of errors on a Stroop task containing incongruent colour-word trials (Tassi et al., 2006). The effects of sleep restriction to 4 h for three nights (Stenuit & Kerkhofs, 2008) or industrial work in 33°C heat (Mazloumi et al., 2014) individually have been associated with impairments in both RTs and errors on incongruent colour-words. Thus for the present data, the increase in the percentage of errors may result from individuals adopting the strategy of increasing their RT performance at the

expense of decreasing accuracy, when under combined conditions of sleep restriction and heat. Regardless of being instructed to simply, ‘respond as quickly and accurately as possible’.

Results for the sleep restriction condition showed no change in errors and an improvement in RTs for incongruent colour-words suggesting that sleep restriction alone has a minor effect on non-executive measures of Stroop performance. This is also consistent with other research comparing the sensitivity of cognitive tests to between 3 h and 9 h sleep for 7 consecutive nights and showing no significant effects on Stroop RTs and percentage correct for incongruent colour-words (Balkin et al., 2004). Importantly, practice effects have also been reported during sleep loss protocols with results showing faster RTs to incongruent colour-words whilst the percentage of errors is unaffected (Sagaspe et al., 2006). For the present findings similar results were shown for the sleep restriction condition and in some instances the control condition and this may reflect learning or practice effects.

Finally, for the non-executive measures of the Stroop task, results also showed time of day effects with an increased percentage of errors for incongruent colour-words in the morning trials relative to the late-afternoon and evening trials on experimental days one and three, regardless of the condition. These results are consistent with partial sleep deprivation research showing for both 8 h and 4 h sleep conditions that accuracy decreased on the Stroop task in the afternoon and evening sessions relative to the morning trial (Jarraya et al., 2014).

For the measures of automatic responding on the Go/Nogo task findings showed Go RTs slowed after the first night of sleep restriction and Go percentage correct declined between sleep restriction nights in the sleep restriction condition only. This result is consistent with previous research showing Go/Nogo RTs slowed following two consecutive nights of sleep restriction to 4 h (Stenuit & Kerkhofs, 2008). Impairments in the proportion of correct Go responses and Go RTs were also found following 55.75 h and 31.75 h of complete

sleep loss using the same task (Drummond et al., 2006). The present results also showed Go RTs slowed in the control and sleep restriction plus heat conditions by the final day of the experiment and between experimental/sleep restriction days. The only other research examining the effects of heat and exercise on the Go/Nogo task did not report any difference for Go RTs following 10 min of cycling compared to rest in 35°C air temperature (Ando et al., 2015). For the present results there appears to be a clear effect of sleep restriction on the measures of automatic responding Go RTs and Go percentage correct. Although the impairment in Go RT performance in all conditions over the duration of the experiment are similar to the impairments shown for the PVT measure of automatic responding lapses. One explanation for these findings is that performance on these lower-level cognitive processes may have been influenced by the effect of repeated testing sessions with a moderate to high mental (Wright, Valdimarsdottir, Erblich, & Bovbjerg, 2007) and physical workload over consecutive workdays.

For the Go/Nogo task time of day effects were also found for Go RTs and Go percentage correct revealing that the afternoon trial displayed improved performance compared to the morning trial regardless of condition by the final experimental day. This result is consistent with a previous study on time of day effects and exercise sessions showing Go RT performance was significantly better in the afternoon compared to the morning (Petit et al., 2013). Results also showed poorer performance on the Go percentage correct in the sleep restriction condition in the morning trial compared to the afternoon trial over experimental days. Similarly, Go RTs have been shown to slow in the morning test following a night of complete sleep deprivation as compared to a nights' normal rest (Bougard et al., 2015).

Findings for the executive function of Stroop inhibitory control showed all conditions were faster by the final day of the experiment indicating the sleep loss conditions had little

effect on inhibitory control. This finding is also consistent with applied research showing Stroop inhibitory control performance did not vary in workers obtaining 6 h to 7 h sleep for two consecutive workdays (Barger et al., 2014). Similarly, no change in inhibitory control was reported during the extended 24 h workshift for workers obtaining 1.88 h of sleep in naps although there was a significant detriment for workers obtaining 3.4 h sleep. However this impairment in Stroop inhibitory control was noted to reflect sleep loss in addition to circadian misalignment (Barger et al., 2014). Another study using the forced desynchrony protocol also showed inhibitory control did not vary with increasing time awake although a strong circadian variation was evident, with performance most impaired at a time corresponding to 1 h to 2 h after habitual awakening (Burke et al., 2015). Similarly, for the present results inhibitory control time of day effects were seen in slower RTs in the mid- and late-afternoon trials compared to the evening. These findings suggest a relatively minor effect of sleep loss on Stroop inhibitory control, although may provide support for the circadian modulation of performance.

In contrast to the improvements shown for Stroop inhibitory control, the executive function of Go/Nogo response inhibition showed impaired performance in the sleep restriction plus heat condition with increased errors by the second day of sleep restriction compared to the first. Go/Nogo task performance impairments on response inhibition have also been reported after 23 h of complete sleep loss (Drummond et al., 2006) and also in another version of the task after 24 h of sleep loss (Chuah, Venkatraman, Dinges, & Chee, 2006). Nonetheless, the present findings also showed the sleep restriction condition did not display any impairment for Go/Nogo response inhibition. This finding is consistent with research on sleep restriction to 3 h for one night showing no impairments on response inhibition to fearful faces on an emotional Go/Nogo task (Rossa et al., 2014). Similarly, Go/Nogo response inhibition has been shown not to vary during three consecutive nights of



exposure to noise induced sleep disturbances (Schapkin, Falkenstein, Marks, & Griefahn, 2006a, 2006b) and also between self-rated good and poor sleepers (Breimhorst, Falkenstein, Marks, & Griefahn, 2008).

A limitation of the current study is that repetitious use of the Stroop task can result in a practice effect that may lead participants to develop a “reading suppression response” and could potentially mask the effects of sleep restriction (Sagaspe et al., 2006). Nonetheless, had participants adopted this strategy it would be expected that incongruent and congruent trial RTs would not differ significantly (Cain, 2011). However, results showed RTs were longer for incongruent compared to congruent trials consistent with the standard Stroop effects (MacLeod, 1991) indicating that performance on the task continued to require inhibitory control (Cain, 2011).

In conclusion for lower-level cognitive PVT measures, findings showed declines in both sleep restriction conditions over sleep restriction days. For the measures of automatic responding on the Go/Nogo task there was a clear effect of sleep restriction resulting in impairments on Go RTs and Go percentage correct. For the executive function of Stroop inhibitory control, performance improved in all conditions over the experiment. In contrast for the executive function of Go/Nogo response inhibition findings revealed for the sleep restriction and heat condition impaired performance between days of sleep restriction. In real-world firefighting settings these results highlight a risk where firefighters may be sleep deprived or sleep deprived in the heat and require fast response times to evade hazards on the fireground. For example, a lapse in attention might be the difference in dodging falling debris such as a tree or structure. Higher-order cognitive capacity such as maintaining situational awareness is also critical for health and safety on the fireground and can be compromised. An example of this is being vigilant to secondary environmental cues while performing the primary task. Since the effects of heat are often inseparable from dehydration and this has

also been identified as another major stressor of wildland fighting (Ruby, Schoeller, Sharkey, Burks, & Tysk, 2003) future research should consider the effects of sleep restriction, temperature and hydration on cognitive performance either in firefighters or in the laboratory.

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